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Implementation of a student-customized integrated upper-level chemistry laboratory course

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ABSTRACT

The implementation of an integrated approach to upper-level undergraduate chemistry laboratory instruction that incorporates student choice both in the selection and sequencing of the experimental work is presented. The approach involves combining laboratory work in several traditional sub-disciplinary areas of chemistry in a single course. Experimental work in emerging areas of chemistry is also incorporated, as are experiences intended to capture an interdisciplinary approach. Logistical affordances, the nature of the resulting learning environment, student responses, and faculty experiences are explored through analysis of curriculum documents and the use of student surveys. The work reveals several strengths and weaknesses in terms of logistics and learning environment, insights into how students engaged with the course and the aspect of choice, and associated benefits and challenges for faculty members. Implications for practice are presented with the aim of informing educators and institutions considering or adopting a similar approach.

KEYWORDS

Upper-division undergraduate, curriculum, interdisciplinary / multidisciplinary, hands-on learning / manipulatives, laboratory instruction, nonmajor courses.

INTRODUCTION

Laboratory experiences are a crucial component of teaching and learning in chemistry at the undergraduate level. There exist many different instructional aims for and styles of laboratory courses (for overviews see Domin [1] and Reid and Shah [2, 3]). In terms of organization and curriculum, such courses may be linked to classroom-based courses, stand alone, focus on a single area of chemistry, or focus on certain parts of the scientific process. Here the focus is upon 'integrated' models for laboratory instruction, where 'integration' refers to the bringing together of two or more traditionally disparate areas of chemistry in laboratory experiences.[4] At our institution, four series of upper-level undergraduate laboratory experiments, each focusing on a specific area of chemistry, have recently been combined into a single, standalone course. Prior to this reformation effort, these were a component of classroom-based lecture courses in four 'traditional' sub-disciplines of chemistry (analytical, inorganic, organic and physical). As well as the four traditional areas of experimental activity, the course includes experiments which draw upon emerging areas of chemistry and experiments that bridge two or more of the traditional sub-disciplines of chemistry.

The reformation effort was in part intended to address (a) logistical constraints such as an increase in course enrollment and in the diversity of degree programs served by the course, and (b) pedagogical ambitions such as providing an instructional experience more closely aligned with the practice of experimental chemistry in modern academic and industrial settings. In the adopted approach, student choice was also emphasized in an attempt to capture the potential, widely-studied benefits for motivation, engagement, and learning. Students can now exercise choice over the subset of experiments that they complete and how these are scheduled. By incorporating a degree of control and autonomy over their curriculum and schedule, and allowing students to tailor their laboratory work towards their interests, it was intended to enhance the intrinsic motivation of our students.[5]

Aspects of student choice in laboratory settings have been reported previously.[6-10] The different ways that students understand and react to control and responsibility in chemistry laboratory settings has been explored, focusing upon student experiences of exercising choice during a particular experiment.[9] In one context a small class size (8-14 students) supported a flexible approach whereby students were able to adjust their choices throughout the course.[7] In terms of outcomes, it has been reported that student choice in laboratory courses led to increased interest and enthusiasm[7] or commitment,[6] although how this was determined was not made clear in all cases. While Buckley et al. briefly mention the factors affecting student choices in a laboratory setting,[6] the ways in which students engage with and exercise such choice has not yet been documented in detail.

Various delivery models for laboratory instruction in chemistry involving some form of 'integration' have been reported for more than 40 years.[4] This term is used to describe both entire courses[8, 11-15] and individual experiments.[8, 16-17] In terms of courses, a range of implementations of integration have been reported. The term 'integrated' itself has been used to describe the combining of a number of laboratory courses in the same physical space,[16] a program of study combining traditional sub-disciplines of chemistry into a single laboratory sequence extending over the first two years of a degree program,[12-13] a one-term course combining four areas of chemistry and focusing upon advanced techniques,[15] an upper-level course in which students work in groups to complete an extended experimental task,[14] a course combining key skills into a 'core' laboratory sequence,[11] and a course which integrates laboratory work in four sub-disciplines of chemistry within student-led research projects to which successive cohorts progressively contribute.[18] The term 'unified' has been used essentially synonymously and in places interchangeably with 'integrated' to refer to laboratory courses at various institutions.[19-22] In some contexts most or all of the component laboratory experiments involved some element of integration.[12-13] In other contexts, as is the case here, experiments specific to a single sub-discipline are retained alongside those combining distinct disciplinary approaches.[8] The term 'integrated' has also been used to refer to the combining of distinct learning experiences within a single laboratory course.[23]

There exist several reports of laboratory reformation efforts which involve moving to an integrated model, detailing the experience of instructors during such work. Overall, the literature indicates that moving to an integrated model is neither uncontroversial nor straightforward. In terms of the value of using integrated approaches, a range of both benefits and challenges for students and educators have been reported. A 1979 survey to which 34 North American academic departments responded revealed that chemistry faculty perceive both academic and logistical benefits, and philosophical and academic objections to the use of integrated experiments.[16] A 1995 survey which sought to explore the use and longevity of integrated laboratories indicated that while integrated laboratories were generally judged to be superior to non-integrated alternatives in terms of student learning, six out of 12 responding institutions reported that they had stopped or would soon stop using them, citing educator time, engagement and issues around assigning responsibility as reasons for the discontinuation.[4] Similar findings appear in reports of integration initiatives at single institutions.[8, 17, 19] Educators have reported that framing their reformation effort as addressing a specific problem, fostering departmental 'ownership' of the program, supporting faculty members to spend time on the development work, establishing a collaborative body with responsibility for the laboratory program,[12] and considering how to optimize the physical laboratory space[13] appeared to support successful implementation of an integrated delivery model.

Student experiences of integrated laboratory delivery and the perceived benefits have been explored mainly *via* educator perspectives.[4] An educator suggested that an increase in student numbers may have been the result of their integrated delivery model for laboratories.[12] While several accounts of initiatives mention advantages and/or disadvantages for students,[8, 11, 15, 17] and one includes direct quotes from students,[20] detailed explorations of student experiences do not appear to be available in the published literature.

As we have seen, integrated laboratory courses have been offered in a variety of forms over many years. Here we build upon previous reports of such courses in the following ways. Firstly, we present for the first time an integrated delivery model that offers a high degree of student choice and an exploration of how students engaged with that choice. Secondly, we discuss the outcomes of the implementation of this model in our context, adding to previous reports of the benefits and challenges of developing and offering integrated laboratory courses. We discuss logistical affordances, aspects of the resulting learning environment, student responses, and faculty experiences. We do not seek to present evidence of learning or to argue that an integrated approach involving choice is more effective than traditional laboratory courses, or to convince others to adopt such an approach. Rather, the intention is to provide information highlighting potential benefits, constraints, and concerns that those contemplating or planning such a reformation effort may wish to consider.

CONTEXT

The laboratory course presented here is offered by the department of chemistry at a research-intensive, publicly-funded university with around 53,000 undergraduates and 4,900 faculty members. At the time of writing the department comprised of around 50 faculty members with contractual responsibilities for chemical research and teaching, and around 10 faculty members with a focus upon teaching and educational scholarship.

The course serves approximately 300 students drawn from a variety of degree programs, including those majoring in chemistry, biochemistry, general sciences, laboratory medical science, and those completing a combined honours program. Depending upon their degree program, students are enrolled under one of four course numbers, which allows for some tailoring of the number and type of experiments open to the different groups of students.

Five faculty members are responsible for co-teaching the course, each bringing expertise in one of analytical, inorganic, organic, physical, or materials chemistry and supervising those experiments which relate to their expertise, as well as contributing to supervising experiments that are interdisciplinary or novel in nature. Around 60 graduate student teaching assistants (TAs) and four technicians help to deliver the course. The experiments take place in five separate laboratory spaces and a shared instrument facility.

The chemistry majors program in which most of the students in this course are enrolled involves four years of laboratory experiences. In the first year students focus on the scientific process and basic laboratory skills.[24] During their second year they begin to develop discipline-specific skills by completing three laboratory courses of around 30 hours each, in analytical/physical chemistry, introductory organic chemistry, and synthetic chemistry (including organic and inorganic experiments). The course presented here provides their third-year laboratory instruction. In the fourth and final year of the chemistry program, students develop their ability to pose research questions, plan experiments, and report the results. This is done either by completing a combination of traditional experiments, inquiry-based experiments and mini-projects within a teaching laboratory setting, or by joining a research laboratory to complete a project. The chemistry majors program is accredited by the Canadian Society for Chemistry.[25] A summary of how the overall structure of the laboratory component of the degree program aligns with the accreditation guidelines is provided in the supporting information (SI1). Students majoring in other subjects, or combinations of subjects, are required to complete the first-year chemistry laboratory course and at least one second-year chemistry laboratory course appropriate to their major before attempting the third-year integrated laboratory course presented here.

INTEGRATED LABORATORY DELIVERY MODEL

The laboratory delivery model described here involves offering within a single course experiments representing four traditional sub-disciplines of chemistry as well as interdisciplinary experiments, which draw on principles from two of these sub-disciplines. A further type of experiment, referred to herein as 'novel', are representative of scientific fields which may form part of teaching laboratories less frequently. For instance, an experiment of this type sees students assemble a vacuum chamber.[26]

Here we use the word 'experiment' to mean a coherent set of laboratory tasks taking either one (most often), two, three or four (rarely) four-hour periods in the laboratory to complete, along with pre- and post-laboratory tasks. The majority of the 'experiments' are confirmatory exercises which focus upon the learning of and practice in using advanced techniques and equipment, followed by the analysis and presentation of collected samples or data. Students are usually provided with detailed protocols and questions to guide their post-lab analysis. The course comprises 10 analytical, 13 inorganic, 13 organic, and 16 physical chemistry experiments, and seven or eight interdisciplinary or novel experiments. Out of a total of just under 60 experiments on offer, most students complete either 18 or 36 over the course of two terms depending on their program requirements. See SI2 and SI3 for an overview of the experiments offered as part of the course and examples of experimental handouts for students.

Learning goals

The aim is that successful students will have developed proficiency in the following four broad areas, which are similar to the learning goals before this reformation effort: Laboratory skills; written and oral communication; responsibility and professionalism; and integration and application of knowledge/experience (see SI4 A-C and E for details). Furthermore, learning goals relating to the integrated nature of the course have been established. These goals include:

(1) *Become proficient in a range of modern techniques*;
(2) *Develop awareness of the interdependence of the traditional sub-disciplines of chemistry*; and
(3) *Become comfortable in an interdisciplinary research environment* (see SI4 D for details).

We address the first of these aims by requiring students to use approaches and techniques drawn from modern academic and industrial research contexts, such as mass spectrometry,[26] thermogravimetric analysis, glovebox chemistry, and electrophoresis. We address the second and third by including interdisciplinary and 'novel' experiments, which are representative of newer cross-disciplinary fields such as materials science and nanotechnology. When the laboratories were a component of classroom-based courses, experiments in non-traditional fields and with interdisciplinary themes were rarely offered as they did not align with the more narrowly-focused course objectives.

Student choice and scheduling

An important aspect of the third-year course, facilitated by its integrated design, is that students select and schedule their own experiments. Here students choose, subject to certain constraints, both the content (which experiments, from a predetermined collection – see SI2) and the schedule (the order, spacing and frequency of those experiments) of their laboratory training. Students may, for example, opt to complete a greater number of experiments from certain sub-disciplines than from others. This offers students the opportunity to match the content of their course to their interests, and to complete experiments according to a schedule that meets their needs with respect to their other commitments. Scheduling is carried out at the beginning of each term of laboratory work. Students are provided with a descriptive title and brief written description for each of the experiments to inform their choices.

The number and type of experiments completed by each student varies based on the requirements of their degree program. A student specializing in chemistry is required to attend 18 laboratory periods per term, completing at least three experiments in each of analytical, inorganic, organic, and physical chemistry, including one mandatory experiment per sub-discipline, and at least two interdisciplinary or novel experiments. The teaching laboratories are open for a four-hour period on three afternoons per week for two academic terms, and most experiments are available for completion during every period. Each student will be timetabled to attend a subset of those periods (one or two weekly) according to their selected schedule and their course requirements. Figure 1 shows a mock schedule of the first four weeks of a term. Students either work in pairs or alone, depending upon the experiment and timing they have selected. Students are not able to specify who they will work with for an experiment. Consequently, they will generally work with a different laboratory partner for each experiment, may sometimes work without a partner, and may see certain instructors and TAs with less regularity than under the previous delivery model.

The selection and scheduling processes are managed using custom software (Chemistry Laboratories Scheduling System, CLaSS), which was designed in-house. CLaSS is a key tool for this student-customized delivery model. As well as managing experiment selection and scheduling applying the relevant constraints, the software records weekly attendance, generates class lists, and maintains records and student access to grades. The software restricts the number of people who will undertake an experiment on a given day according to the capacity of the relevant equipment, and by allocating sets of the necessary glassware and chemicals to each experiment it can be ensured that the correct resources are always available. Further details of the software are included as SI5, and a report of a similar software is available elsewhere.[10]

A consequence of allowing student choice relates to the sequencing of instruction. In a more 'traditional' model of laboratory instruction, instructors have considerable control over which experiments are completed, in what sequence and with what spacing, whether through a 'round-robin' approach or by having all students complete the same experiments in a pre-determined sequence. Such level of control is potentially supportive of the achievement of particular learning objectives and/or the incremental development of techniques and knowledge. It also allows for synchronization with learning taking place through classroom-based courses. Our integrated model largely restricts our ability to control the sequence of laboratory experiences, although some control can be exerted, for example by assigning pre-requisite experiments for certain laboratory experiences (managed here using CLaSS). However, more generally each laboratory experiment must be viewed as a stand-alone learning experience. It is worth noting that the potentially uneven spacing and interleaving of laboratory experiences of certain types, and the challenges students may face from non-sequential practice may be beneficial for learning. Bjork argues that introducing specific types of challenges (so-called 'desirable difficulties') like interleaving of skills practice into the learning process can improve retention and transfer of learning,[27] and distributing instruction and/or practice over longer periods of time has been shown to improve long-term retention (the 'spacing effect').[28-29] The effect of spacing and interleaving of practice on student learning has not been considered here and represents an area for future work.

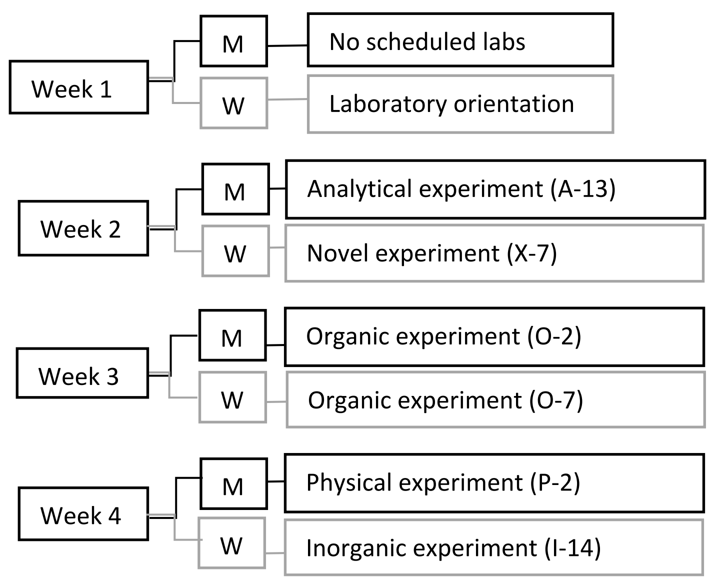

Figure 1. *Mock schedule of the first four weeks of a term for a student timetabled to attend two laboratory sessions per week (Monday (M) and Wednesday (W) in this schedule). Every experiment is scheduled in an order selected by the student. Experiment number codes listed are arbitrary.*

Pre-laboratory preparation

To prepare for their laboratory work, students attend orientation sessions to familiarize them with the laboratory space and procedures. They are required to successfully complete an online safety quiz. As the laboratory course operates independently of third-year lecture courses, detailed background information and references to literature are provided for each experiment. Each experiment involves pre-laboratory exercises which ensure that students have engaged with the background information provided - some involve the preparation of flowcharts, reagent lists, or detailed plans for synthetic procedures, while others require specific questions to be answered. These tasks are checked by an instructor or TA before the student is permitted to begin work. Those not majoring in chemistry and hence having taken only one second-year laboratory course are limited to a subset of experiments involving only those techniques which they have been prepared to use.

Assessment strategies

The course uses a range of in- and out-of laboratory activities to assess student achievement: pre-lab assignments; in-lab oral discussions; sample/data quality measures; written laboratory reports; oral laboratory reports; feedback reflection activities; and a final written exam. Various combinations of these assessments are associated with each experiment, as determined by the supervising instructor. At the time of writing, oral laboratory reports were only used for the interdisciplinary or novel experiments. See SI6 for further details of the assessment strategies.

METHODS

The nature of the resulting learning environment has been explored through the analysis of laboratory curriculum documents and grade records. Laboratory manuals and experiment offerings before and after the reformation have been used to identify the associated changes to the course in terms of curriculum and pedagogy. Anonymized records of grades recorded for individual experiments have been consulted.

Student responses have been explored using online surveys. The custom surveys explored how students responded to the course overall, their perspectives on the interdisciplinary and novel experiments, how they engaged with having choice over the experiments that they completed and their scheduling, and their perspectives on their interactions with classmates. Three main item types were used in the following ways: (i) Ranking items asked students to place options in a rank order based upon particular criteria, without the option to indicate joint rankings; (ii) Likert items asked students to indicate the extent of their agreement with particular statements using a five-point scale ranging from strongly agree or agree through neutral to disagree or strongly disagree; and (iii) open-response items were used and analyzed using emergent thematic coding. Special items were included to identify and discard careless responses. Most survey items were repeated each term and year. Please see SI7 for all student survey instrument items drawn upon in this manuscript (other survey items posed but not relating to this work included those focussed on individual experiments to inform improvements to them).

Survey data were collected over nine terms between 2013 and 2017. To capture both initial impressions and overall opinions of the course, data were collected during the first week of class and during the week after all laboratory sessions were completed each term. Surveys remained open for seven to 10 days. All enrolled students were invited to participate. In recognition of their time and thought, and to encourage participation, students received 0.5% towards their course grade for completing each survey. Students were made aware that an independent researcher would review the responses and that instructors would only see responses after any identifying information had been removed. Our average response rates on the start- and end-of-term surveys were 67% (SD=11) and 68% (SD=9), respectively. Throughout we use 'n' to represent the number of responses to survey items.

The study adhered to the Behavioural Research Ethics Board approved protocol (H14-01328).

IMPLEMENTATION OUTCOMES

The level of success of the reformation effort is now explored through a consideration of the logistical affordances of the model, aspects of the resulting learning environment, student responses to the delivery model, and faculty experiences.

Logistical affordances

Positive aspects of the reformation effort relate to the logistical success that has been achieved - the course operates smoothly under conditions of considerable complexity (multiple laboratory spaces; multiple faculty members; many experiments; large student enrollment; conditions of student choice). This complexity has been successfully accommodated in part through the development of custom software (CLaSS). The model is supported by having several of each characterization instrument (UV-Visible spectrophotometer; FTIR) and a shared instrument facility housing further instruments including an NMR spectrophotometer.

The model supports efficient use of separate laboratory spaces; it has increased the maximum capacity of the laboratories by ~ 75-150 students per week. The approach allows maximum use to be made of teaching laboratory capacity by students drawn from different degree programs. Making all laboratory places available at all times to students from various degree programs means that limitations posed by uneven program enrollments and uneven capacity of laboratory teaching spaces across various disciplines are lifted. This laboratory delivery model is most efficient when the overall student demand is equal to or just less than the overall laboratory places available. If the overall demand is significantly less than the maximum capacity, inefficiencies arise. When planning for the term, it is necessary to assume that all offered places will be taken, and thus to prepare materials and equipment and to schedule TAs accordingly. In practice, the occupancy can vary significantly across the term, which can make planning difficult.

Learning environment

In reforming the laboratory course, it was aimed to develop advanced laboratory skills as before, as well as to provide an experience aligned with emerging areas of chemistry and interdisciplinary ways of working. Table 1 summarizes the changes in the instructional laboratory experiences offered during third year for students majoring in chemistry.

Table 1*. Instructional laboratory experiences offered during third year for students majoring in chemistry before and after the reformation effort, with an indication of ongoing developments. [a]Offered from 2018–19, see ref.[30].*

Stage	Discipline-specific experiments	'Novel' and 'Interdisciplinary' experiments
Before reformation effort	10 analytical, 10 inorganic, 8 organic, and 10 physical chemistry experiments; 38 completed in total	None offered
After reformation effort	10 analytical, 13 inorganic, 13 organic, and 16 physical chemistry experiments; with most running as before the reformation effort; minimum of 3 completed per sub-discipline; maximum of 32 completed in total	7 experiments offered; minimum of 4 completed of this type
Ongoing development	No additional experiments currently in development	1 additional experiment[a]

From this comparison, the overall amount of discipline-specific training is reduced slightly after the reformation effort (from around 152 hours to around 128 hours). This is not an automatic consequence of the reformation and can be adjusted based on laboratory capacity and accreditation requirements. Students may also now skew their experience towards a given sub-discipline. The sequencing of the discipline-specific training has changed significantly. It is not straightforward here to compare discipline-specific *learning* before and after the changes, as changes elsewhere in the curriculum mean that a suitable comparison group does not exist.

We now consider the extent to which students can be expected to have met the learning goals relating to emerging areas of chemistry and interdisciplinary ways of working (see SI4 A-D). The course design is based upon the assumption that by providing students with first-hand experience in using these modern techniques and by combining activities drawn from different sub-disciplines in a single laboratory experiment, students will be better prepared to engage with these techniques and to transfer their knowledge across sub-disciplines in the future. Measures of such learning gains are however beyond the scope of this work, and here we focus upon the nature of the learning opportunities made available through this reform effort. Table 1 summarizes the 'novel' or 'interdisciplinary' experiments that have been developed. Students enrolled on the chemistry majors program carry out a minimum of two of these experiments each term - learning opportunities which were not available before course integration. Implementation of this delivery model has supported the development of 'novel' laboratory experiences in particular. The standalone nature of the course supports the offering of experiments not typically part of laboratory courses in the traditional sub-disciplines and those attached to classroom-based courses. Eight such experiments have been developed so far.

Table 2 summarizes the key features of the novel and interdisciplinary experiments. Interdisciplinary experiments bring together synthesis and analytical or physical chemistry methods. In one experiment students prepare opals and then characterize the particle size and composition using atomic force microscopy (AFM) and infrared spectroscopy (FTIR). In a further experiment synthesis is followed by a study of decomposition kinetics. Novel experiments involve topics not typically falling within laboratory sequences accompanying disciplinary lecture courses, for example the construction of a vacuum chamber, the preparation of a catalyst recently developed through the research program of a faculty member in the department, and experiments situated in modern materials science.

Student responses

Course as a whole

To explore student perspectives of the course delivery model overall, students were asked to list one or two benefits they believed were associated with offering experiments from the four traditional sub-disciplines in a single course. While all students were surveyed, analysis for this item and the item described in the section 'Interdisciplinary and novel experiments', was limited to the responses from those students majoring in chemistry and at the end of their second term of the course. We reason that these students are best placed to assess the course and its interdisciplinary nature as they have complete two full terms of the course and have completed at least four interdisciplinary or novel experiments.

Students could identify a range of benefits of the delivery model. The most frequent response described a sense of a diversity of experience, in terms of content, perspectives, instructors, or techniques, within a single course (44%, n=78). The next most common response described freedom of choice in selecting experiments and creating a schedule as being a beneficial aspect of the delivery model (17%). Other common responses spoke more directly to the integrated nature of the course, describing learning about or creating connections, integrating knowledge, referring to the interdisciplinary experiments, or describing the convenience of taking a single laboratory course and therefore only needing to manage a single schedule for all laboratory work.

Table 2*. Nature of novel and interdisciplinary experiments developed as part of this reformation effort.* [a]*See ref.* [26]; [b]*Offered from 2018–19, see ref.* [30].

Experiment title	Brief description	Key features
Introduction to Vacuum Science and Mass Spectrometry[a]	Students assemble a vacuum chamber equipped with a mass spectrometer. They collect and analyze the mass spectra of: vacuum, air and a halogenated organic compound and attempt to identify the halogenated compound.	Students gain experience in mass spectrometry and vacuums systems which is not typically part of undergraduate lecture or laboratory courses in physical chemistry.
Synthesis of “Schafer’s Ti Catalyst” and Hydroamination Reaction	Students synthesize *Schafer's Ti Catalyst* and use it as a precatalyst. Students will learn to use Schlenk techniques and an inert atmosphere glovebox. Once synthesized, the complex is used to carry out a small-scale intermolecular hydroamination reaction.	Students are exposed to the outcomes of the research program of a faculty member in their department.
Laser Photoionization Time-of-Flight Mass Spectrometry	Students use a laser to ionize molecules in a vacuum system and separate the ions by time-of-flight mass spectrometry. They study the fragmentation of toluene by mass spectrometry when ionized with 266 nm UV laser light.	Students gain experience in time-of-flight mass spectrometry and lasers which is not typically part of undergraduate lecture or laboratory courses in physical chemistry.
Synthesis and Characterization of Switchable Superhydrophobic-Superhydrophilic Polypyrrole Surfaces	Students synthesize a polypyrrole film and study its water repellant properties and composition. Then they switch the response of the surface to water using an electrochemical stimulus.	Students gain experience in materials chemistry which is not typically part of undergraduate lecture or laboratory courses. The experiment combines synthesis and analytical methods.
Preparation of silica-based opals from molecular precursors	Students prepare silica microspheres of varying sizes and characterize particle size and composition using atomic force microscopy (AFM) and infrared spectroscopy (FTIR).	Students gain experience in materials chemistry which is not typically part of undergraduate lecture or laboratory courses. The experiment combines synthesis and analytical methods.
Synthesis and Characterization of Poly (methyl methacrylate) (PMMA) (four lab periods)	Students pose a research question, research background information, and submit a procedure that will answer their research question. A TA provides feedback on their procedure. They synthesize PMMA in an inert atmosphere via Schlenk techniques and then characterize their polymer to answer their research question.	Students gain experience in materials chemistry which is not typically part of undergraduate lecture or laboratory courses. The experiment combines synthesis and analytical methods. A guided-inquiry approach is adopted.
Introduction to Photochemical Upconversion (four lab periods)	Students synthesize a palladium (II) tetraphenylporphyrin complex and study the upconversion that occurs between the palladium complex and 9,10-diphenylanthracene.	Students gain experience in photovoltaics which is not typically part of undergraduate lecture or laboratory courses.
Synthesis and Decomposition Kinetic Studies of Bis(lutidine)silver(I) Nitrate Complexes[b]	Students synthesize bis(lutidine)silver(I) nitrate complexes and then carry out kinetic studies of their decomposition.	Brings together synthetic (inorganic) and physical chemistry.

Interdisciplinary and novel experiments

In terms of student perspectives towards undertaking one or more of the interdisciplinary or novel experiments, when asked *via* a survey distributed during the week after all laboratory sessions were completed each term to describe any perceived benefits to their learning arising from completing experiments of this type the most frequent responses, making up half of all responses (n=57), were representative of:

(i) Allowing the student to learn new or modern techniques (18%);
(ii) providing the opportunity to combine different concepts and sub-disciplines in a single experiment (18%); or
(iii) that the experiment offered the opportunity to present an oral laboratory report (16%)

Other common responses demonstrated that students perceived that the following were beneficial for their learning:

(i) Being provided with a chance to explore topics that were not drawn from the traditional sub-disciplines of chemistry (11%);
(ii) being able to see how different sub-disciplines work together (7.0%); and
(iii) carrying out laboratory work that was more relevant to "real" research or industrial contexts (7.0%).

Choice

A goal of our reformation effort was to capture the potential benefits of offering students choice over the content and scheduling of their learning experiences. Here we consider the extent to which this goal was met by considering student responses to this aspect of the delivery model and the ways in which students engaged with the choices they were offered. By incorporating some degree of choice and personalization in the laboratory course experience, the goal was for students to experience an enhanced sense of control and increased intrinsic motivation for their studies, ultimately helping their learning in this course. While others have noted that choice is a positive feature in instructional laboratory settings,[6-7] how students engage with and exercise this choice has not been explored in detail.

While allowing student choice was mainly intended to allow students to build an experience that interested them, in practice a range of factors may have influenced their selections. Motivations for experiment selection were investigated by asking students to report factors that influenced their choices *via* a survey distributed during the first week of classes, soon after they had made their selections. A list of eight possible factors expected to play a significant role in their decisions in this context was provided (see Figures 2 and 3) and students were asked to rank the top four of those factors in terms of the extent to which they influenced their choice of experiments. The option to select 'other' to indicate that another factor was influential was also provided.

Figure 2 shows the proportion of respondents (n=481) who selected each of the eight provided factors (or 'other') as their most influential factor. The factors most often selected were: 'Desire to learn or practice certain techniques' (selected by 24% of respondents); 'distributing workload evenly' (18%); 'maximizing grade' (18%); and 'minimizing workload' (18%). The pattern of responses is broadly similar for students majoring in chemistry and those completing other degree programs, although minimizing workload is relatively more important to those majoring in chemistry, while maximizing grade is relatively more prominent for those majoring in other subjects. These four factors were also most often selected as one of the four most influential factors, as shown in Figure 3: 'Distributing workload evenly' was selected by 71% of respondents; 'desire to learn or practice certain techniques' by 69%; 'maximizing grade' by 63%; and 'minimizing workload' also by 63%. The other four factors were ranked highly with less frequency, indicating that sequencing of experiments and working with a particular laboratory partner were generally perceived as less important than technique-learning and workload and grade considerations.

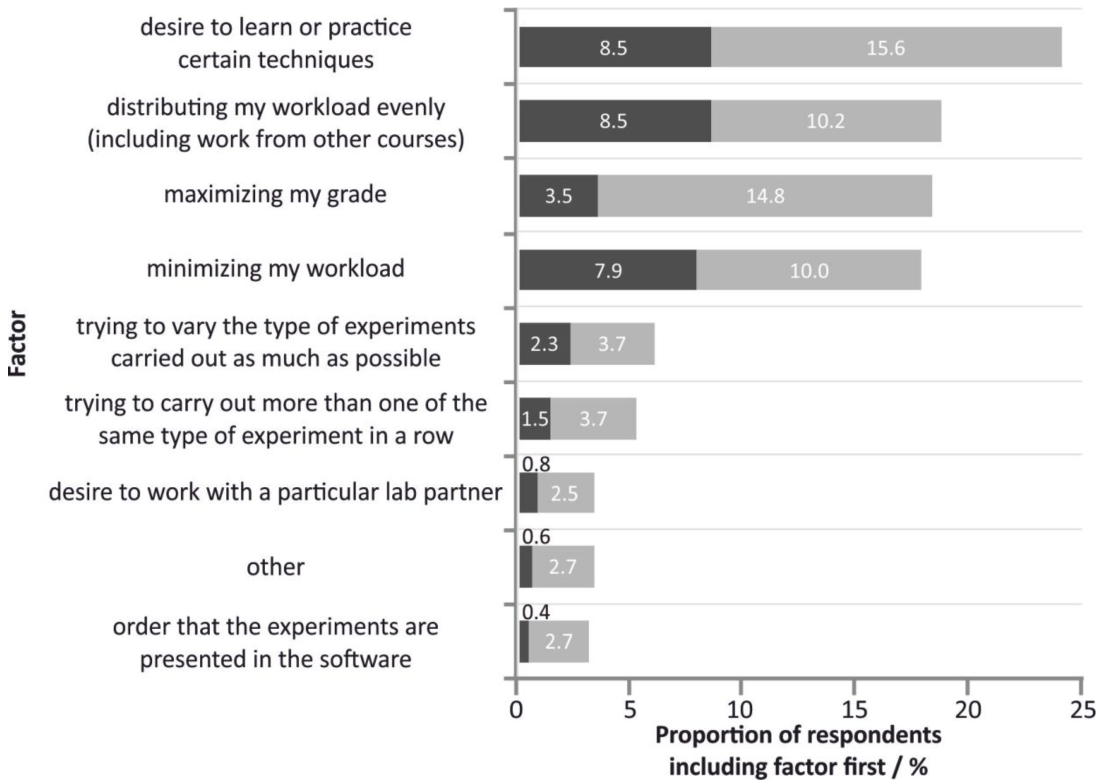

Figure 2. *The percentage of all respondents (n=481) who selected each factor as their top influencing factor. Responses from students majoring in chemistry (n=164) are shown in dark grey while those from all other students (n=317) are shown in light grey. The data include some responses from the same students collected during two terms. 'Type' here is defined as the relevant category of experiment (analytical, inorganic, organic, physical, interdisciplinary or novel).*

It is encouraging to see that a desire to learn particular techniques played an important role in student selections of experiments, as this suggests that this approach may allow students to be guided by their intrinsic motivation in making their decisions. We were not surprised to see workload-related factors being reported as important for experiment selection. Workload has been consistently raised as a concern by students both in this institution in general and within this course specifically. An ability to manipulate workload *via* distribution or minimization arises in this context mainly through differences in the reporting procedures for experiments drawn from the various sub-disciplines. Analytical and physical chemistry experiments typically involve more extensive post-laboratory data analysis and reporting procedures than inorganic and organic chemistry experiments. When students were surveyed about the time spent on a 'typical experiment', the median total time reported (including in- and out-of-laboratory) was just over 10 hours (n=377). For a student majoring in chemistry and completing two experiments each week this is indeed a particularly substantial commitment. It seems reasonable that under these conditions, personal interest and learning goals may compete with workload concerns. This balancing of 'learning' *vs.* 'practical' factors has been reported previously in the context of a laboratory course.[6]

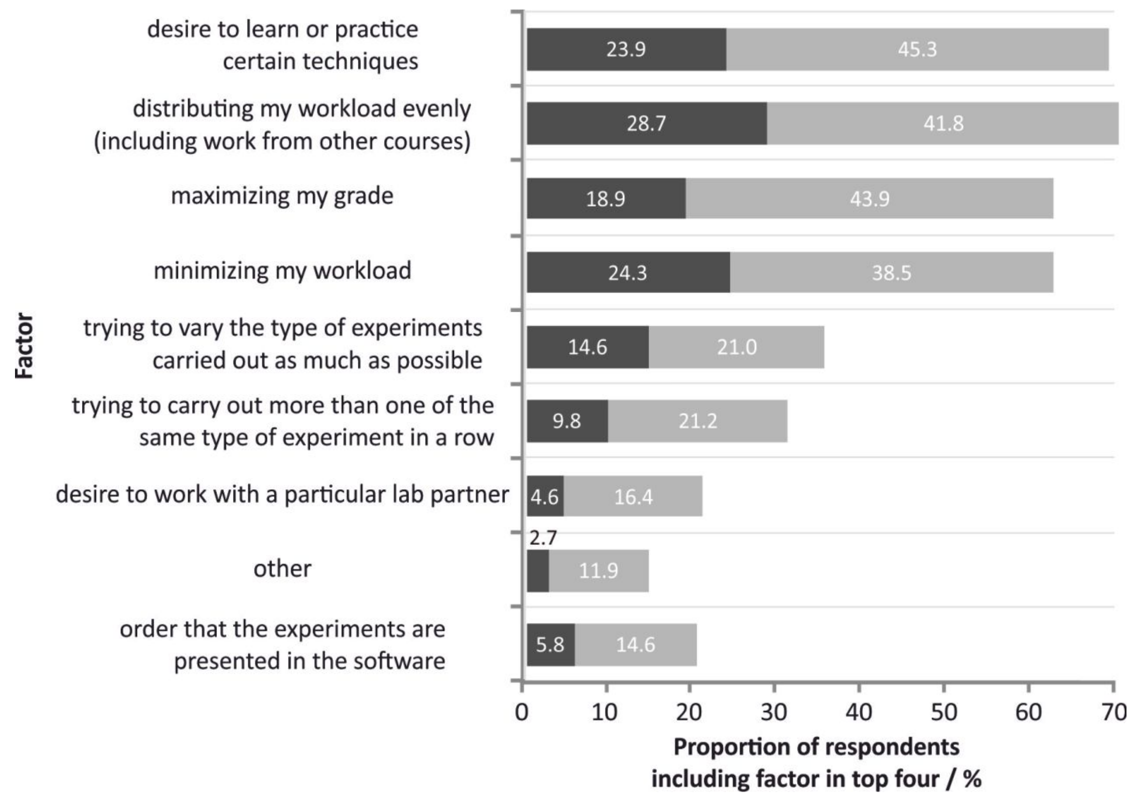

Figure 3. *The percentage of all respondents (n=481) who selected each factor as one of their top four influencing factors. Responses from students majoring in chemistry (n=164) are shown in dark grey while those from all other students (n=317) are shown in light grey. The data include some responses from the same students collected during two terms. 'Type' here is defined as the relevant category of experiment (analytical, inorganic, organic, physical, interdisciplinary or novel).*

Figure 4 shows the changes in the aggregate responses regarding the reported top four most influential factors when comparing students at the beginning of their first term of the course and those who are returning for their second term. Positive differences indicate the factor was reported as of relatively high influence by a greater number of 'returning' than 'new' students. The biggest increases concern workload – minimizing it or seeking to distribute it evenly. The biggest decreases concern a desire to learn or practice certain techniques and trying to vary the type of experiments carried out as much as possible. The directions of the changes are the same for both chemistry majors and those majoring in other subjects for all but one factor.

It is worth noting that students returning for the second term of the course have already completed some experiments and so have fewer to choose from when selecting experiments, and this could be expected to influence the factors influencing their choice. For example, trying to vary the type of experiment and/or the desire to learn certain techniques may be less achievable or relevant during the second term. The rising influence of workload considerations could however indicate that 'practical' or instrumental factors become more prominent for students as the academic year proceeds.

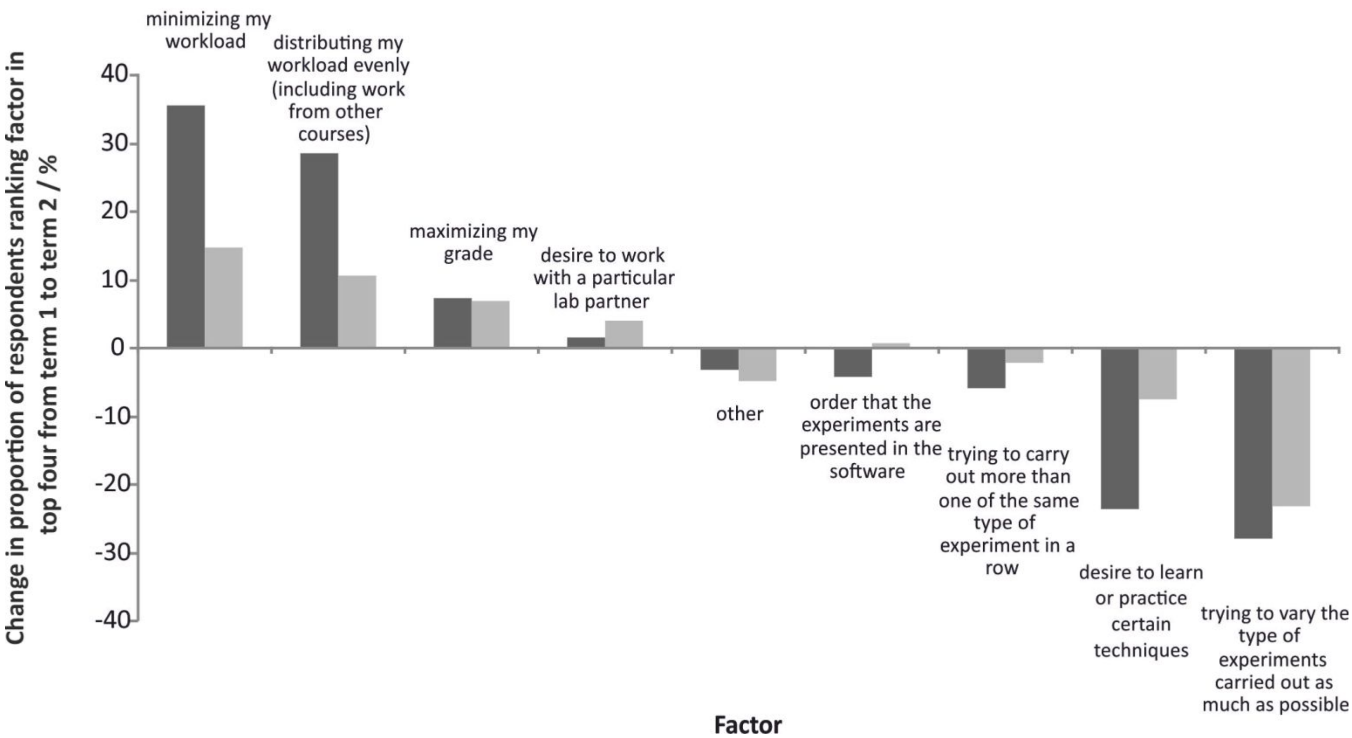

Figure 4. *Changes in the aggregated responses of students at the beginning of their first term of the course and those who are returning for their second term. Positive differences indicate that the factor was more frequently chosen as a 'top four' factor by returning students. Responses from students majoring in chemistry (first term students n=72, returning students n=92) are shown in dark grey while those from all other students (first-term students n=197, returning students n=120) are shown in light grey. The factors are presented in order from the most to least positive change recorded for those students majoring in chemistry.*

To further explore how students engaged with choice, they were asked to describe any additional information that would have been helpful for choosing their experiments on surveys circulated at the start of both terms during the 2015/16 academic year. Over these two surveys, 97 students responded to this item and 81 relevant responses were identified by thematic coding. Student responses to this item provide insight into whether the list of eight provided factors was sufficiently complete. The most prominent theme, representing 30 responses, described requests for further details about experiments such as laboratory procedures or a full copy of the laboratory manual. A similar response mentioned by 11 respondents revolved around having a list of techniques and instrumentation that would be used in each experiment. The following student comment is representative of this theme:

> *"Clear+concise list of techniques used in each experiment [...] would enable us to choose a maximum amount of different techniques to learn... or in some cases minimum I guess if there's people who aren't willing to learn new techniques [for] every experiment".*

11 responses expressed a desire to know the assessment process for each experiment, for example the type of report required. Less frequent responses (one to three responses) included knowing what prior knowledge would be required, the level of difficulty of the experiment, the number of students that are taking an experiment on a given day, and information about the connection between the experiment and daily life or career options.

While most of the responses described above correspond to factors included in the list of factors we offered in our survey (for example interest in techniques, and workload), responses about prior knowledge and the number of students registered to take an experiment on a given day were not represented and may benefit from further exploration. For example, prior knowledge may relate to confidence to complete an experiment successfully and may be particularly important in courses such as this one, which serve cohorts drawn from a range of degree programs.

To explore the extent to which the possible benefits of incorporating student choice were realized in this setting, all students during 2013 and 2014 were asked *via* a survey distributed during the week after all laboratory sessions were completed each term about the perceived benefits of deciding the sequence in which they carried out their experiments. 53% (n=296) of respondents strongly agreed or agreed with the statement 'deciding the sequence in which I carried out experiments increased my motivation', while 55% (n=298) strongly agreed or agreed with the statement 'deciding the sequence in which I carried out experiments was helpful for my learning'. For both statements, 30% of respondents selected 'neutral'. These responses suggest that allowing some choice over curriculum and sequencing may not have been strongly valued by the cohort overall, and hence the potential benefits of offering choice may not have been fully captured in this context.

Interactions with classmates

Finally, we consider the perceived influence of the course delivery model with respect to working with others. As explained above, in this course students will generally work with a different laboratory partner for each experiment and sometimes work without a partner. A previous study by Lyall revealed positive student perceptions towards working independently in a chemistry laboratory, with students forming informal collaborative groups as needed to solve problems.[31] These more fluid peer interactions may be closer to the situation in this course than was the case before the course was transformed, when students worked in static pairings in each separate laboratory course. To explore the perceived effect of this situation on both their learning of chemistry and their development of teamwork skills, we asked all students during 2013 and 2014 *via* a survey distributed during the week after all laboratory sessions were completed each term whether they felt that working with different laboratory partners was helpful for their learning of chemistry techniques and knowledge. Only about half (54%) of respondents (n=281) strongly agreed or agreed that this was helpful and another 30% were neutral; however, 74% (n=280) strongly agreed or agreed that this was helpful for developing their teamwork skills (20% were neutral). It appears students feel more positive about this feature of the course in terms of developing the ability to work with others than with respect to their learning in chemistry. These responses suggest a need to carefully consider and more fully explore the perceived and actual impacts of rotating laboratory partners.

Faculty experiences

In terms of consequences for faculty time, effort and ways of working, developing and delivering this course relies upon a functioning interdisciplinary teaching team. There are clear advantages of this teaching structure, such as being able to develop new experiments that draw from the expertise of the team rather than individual instructors. This advantage has been capitalized upon to some extent (see Tables 1 and 2).

At the same time, the reformation effort was not straightforward. It required a considerable investment of time and effort in collaborative course re-design, consensus-building, and adjusting to new ways of working (such as developing interdisciplinary learning experiences), as has been noted by others who have delivered similar team-taught courses[32-33] and integrated laboratory courses.[16] Navigating instructor differences and building effective team-working processes required a significant time investment. Here, a course coordinator role was established as an administrative role without allocated working time, rather than as a substantial role involving responsibility for leadership. The establishment of a course leader role which was supported by an appropriate mandate to take decisions following consultation and by an allocation of working time for such responsibility may have been more effective.

SUMMARY, IMPLICATIONS FOR PRACTICE, AND AREAS FOR FUTURE DEVELOPMENT AND STUDY

Summary

This article has presented an integrated laboratory delivery model for upper-level undergraduate chemistry laboratories in which student choice regarding both the experiments completed and their scheduling is a key aspect of the design. The work reveals several strengths and weaknesses in terms of logistics and learning environment, insights into how students engaged with choice, and associated opportunities and challenges for faculty members.

This delivery model is supportive of efficiently accommodating large enrollments and those drawn from multiple degree programs. Efficiency is highest when the enrollment approaches the maximum course capacity. The model is supportive of developing and offering interdisciplinary and novel experiments.

From the perspective of learners, as has been noted in previous work students in this course identified several perceived benefits associated with the integrated delivery model. The ways in which students engage with choice in a laboratory course setting has not been explored in detail previously. Here a little over half of the students reported that choice increased their motivation or helped their learning. Our data showed that there are a variety of factors that students consider when they select their experiments. While desire to learn or practice certain techniques was most frequently reported as the most important factor influencing student choice, the data do not support the notion that most students are mainly motivated by interest in the content of the experiments alone – workload and grade considerations are also frequently reported as important. Changes in the factors reported as influential suggest that workload issues become more important over the course of the academic year. While a majority of students agreed that working with different laboratory partners was effective for developing teamwork skills, only around half agreed that this was helpful for their learning of chemistry.

In terms of faculty experience, the experiences of the faculty members are aligned with published reports of similar reformation efforts. As noted by others and reiterated here, developing and delivering this type of laboratory course is challenging for the educators involved, owing to the time and coordination efforts that must be invested.

Implications for practice

Several tentative recommendations can be made based upon our experience and findings. Firstly, it is recommended that departments and individuals do not underestimate the time and adjustments to working practices and preferences that a reform effort such as this may demand. Supporting this need for time and considering the ways in which institutional norms may support or hinder such efforts would be likely to be beneficial, and may support the development of a greater number of interdisciplinary laboratory experiences.

Secondly, our findings indicate that a range of factors influence the choices made in instructional laboratory settings by undergraduate students. If it is desirable to fully capitalize on the potential benefits of choice in terms of fostering personal interests and intrinsic motivation in experimental work, it is recommended that workloads and other practical factors be equalized across experiments to allow factors relating to interests to compete more strongly with more practical matters. This could be achieved by equalizing post-laboratory task loads, incorporating these tasks into 'in-lab' time, or allocating different numbers of credits to different experiments. Our data indicate that choices may become more 'practical' as the year wears on, which may suggest that the timing of experiment selections is worthy of consideration. It may also be worth considering ways in which personal interest may be more effectively engaged during the experiment selection process. For example, along with written summaries describing each experiment, connections to real-world contexts or a survey of skills and techniques offered across the course may be helpful for students.

In a context where laboratory student pairings are constantly changing, it may be beneficial to manage student perceptions of this situation, and to provide support and guidance to students in how to most effectively work with new people in order to safeguard learning of chemistry knowledge and skills. Explicit guidance of this type may also maximize the potential benefits of this arrangement for developing teamwork skills.

Areas for future development and study

This work suggests several avenues for future development and study. As mentioned above, a range of models for integrated laboratory courses have been developed, and work considering how to systematically compare the learning experiences and outcomes would be welcome. Learning through interdisciplinary experiments would also benefit from further study to develop an understanding of the cognitive processes involved in, for example, combining synthetic and analytical or physical techniques in one coherent experimental task. The development of approaches to measuring such learning would be welcome, building on work in other disciplines (see for example [34]). Taken together, such work would contribute to a firmer basis for the design of interdisciplinary laboratory courses in the chemical sciences.

The effects of spacing and interleaving of practice on student progress is of interest in terms of understanding how students learn in chemistry laboratories. A future study could adopt an experimental design in order to determine the impact of choice on engagement and learning. The pairing of students during experiments could be considered and controlled to a greater extent, for example to explore the potential benefits of pairing students with different disciplinary expertise. Previous work has illustrated how the diverse expertise of students with differing academic backgrounds can be brought together in a meaningful way to address a scientific problem.[35]

Within this delivery, model students may encounter particular instructors and TAs with less regularity, perhaps seeing them twice a week for a few weeks and then not again for many more, rather than, say, once per week of an entire semester under the previous system. This may influence the development of any teacher-student relationship between them. This aspect of the delivery is worth considering to understand how to support effective relationships under these conditions.

ASSOCIATED CONTENT

SUPPORTING INFORMATION

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.XXXXXXX.

A table providing an overview of the laboratory components of the four-year degree program in chemistry and a description of accreditation guidelines; a table with an overview of all the experiments offered to the students in this integrated course; examples of laboratory handouts for each type of experiment; course level learning objectives for this integrated course; details of the scheduling software, CLaSS; breakdown of the assessment strategies used in this course; survey instrument used for collecting data (PDF).

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